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Computational Simulation of the Formation and Material Behavior of Ice

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COMPUTATIONAL SIMULATION OF THE FORMATION AND MATERIAL BEHAVIOR OF ICE

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SUMMARY

Computational methods are described for simulating the formation and the material behavior of ice in prevailing transient environments. The methodology developed at the NASA Lewis Research Center was adopted. A three-dimensional finite-element heat transfer analyzer was used to predict the thickness of ice formed under prevailing environmental conditions. A multifactor interaction model for simulating the material behavior of time-variant ice layers is presented. The model, used in conjunction with laminated composite mechanics, updates the material properties of an ice block as its thickness increases with time. A sample case of ice formation in a body of water was used to demonstrate the methodology. The results showed that the formation and the material behavior of ice can be computationally simulated using the available composites technology.

INTRODUCTION

Ice forms in nature in various ways and comes in contact with manmade structural systems and their components. The formation of ice on structures can cause undesirable loading which affects their performance. In severe environments with constantly changing conditions such as temperature and time, the properties of ice vary significantly. To effectively counteract damaging ice effects, it is necessary (1) to understand the mechanism of ice formation, (2) to identify the different variables (factors) and environmental conditions that affect the properties of ice, (3) to characterize the material properties of ice, and (4) to analyze how the ice properties are affected by the combination of (1) to (3).

Experimental investigations of the material behavior of ice are expensive, test specific, and not always reliable. For instance, the strength of ice as measured under laboratory conditions can be different by an order of magnitude from multiyear sea ice (ref. 1). General purpose computational simulation models are needed for a cost-effective and reliable quantitative assessment of the material behavior of ice. The NASA Lewis Research Center has been developing computational simulation methods and corresponding computer codes for more than two decades to analyze composite materials and/or structures (ref. 2). These methods and codes are applicable for evaluating the behavior of ice. The objective of this report was to demonstrate the capability of these computer codes to predict the thickness of the formation and the properties of ice in prevailing environments. Chosen for the demonstration was a sample case of ice formation in a body of water to evaluate (1) the time-variant thickness of ice formed under prevailing environmental conditions and (2) the mechanical and thermal properties of ice at different temperatures through the ice thickness.

FUNDAMENTAL CONSIDERATIONS

A sample case of ice formation in a body of water was chosen for the present study. When a body of water is exposed to subfreezing temperatures at its top surface, a temperature gradient develops throughout the water depths (fig. 1). The formation of ice occurs gradually: as the top water layer reaches the freezing temperature, it becomes ice. The temperature gradient is continuously changing throughout the water depth. As the second layer of ice forms, the temperature in the first layer decreases further, causing the material properties of the two layers to be different. Hence, a block of ice formed over a period of time consists of several layers of ice having different material properties and a different temperature profile for each layer. Consequently, the mechanism of ice formation governs the material properties. To evaluate the properties of the ice block, it is convenient to simulate the ice formation process layer by layer because each layer has its own mechanical and thermal properties. Well-known laminate theories can then be used to determine the properties of the ice block for the individual layers since the overall ice block characteristics depend on the integrated material behavior of the individual layers. As the temperature decreases, ice becomes less dense, harder, and stiffer.

The structural behavior of ice depends on many variables including load, loading rate, time, scale, and environmental conditions. The environmental conditions such as temperature may change by the time the first layer of ice is formed; the next layer thus forms under different environmental conditions. The impurities in water may lead to inclusions in the ice, altering its behavior. The quantification of the effect of all these variables on the behavior of ice required an all-inclusive simulation model. One such model, the multifactor interaction model (MFIM), successfully used to simulate the complex nonlinear behavior of metal matrix composites (ref. 3), was used to simulate the ice behavior. MFIM is of the form

$$\frac{P}{P_o} = \prod_{i=1}^{n} A_i^{m^i} \tag{1}$$

$$A_i = \left(\frac{A_F - A}{A_F - A_O} \right)_i \tag{2}$$

where P is any property of the material (ice); n is the number of primitive variables; A is the primitive variable (factor such as temperature); i is the index for the primitive variables; the superscript m^i is the material exponent which represents that property behavior path from the reference to the final value; and the subscripts F and O refer to the final and reference values, respectively.

The multiplicative form of the MFIM model automatically accounts for the interactive effects of the individual factors. Obviously, additional factors of a similar form can be added for new variables that can change the material behavior. The MFIM is applied at the primitive (most basic or fundamental) variables scale. Thus, the independent effect of each primitive variable is accounted for at the lowest material scale. The effect on higher scale variables is assessed by using the physical behavior of the material at its various scales. The behavior of ice does not conform to traditional mechanics theories: ice is not purely elastic, viscous, or plastic (ref. 1). The MFIM enables the characterization of a completely general material behavior via a single computational model. In the present report, we demonstrate the temperature and time effects. Other effects such as impurity content can be demonstrated similarly.

COMPUTATIONAL SIMULATION PROCEDURE

The available computational methods were developed based on naturally exhibited physical behavior of composite materials and/or structures. These methods are capable of simulating the ice formation process layer by layer. The layers can be (1) homogeneous as in the case of granular ice usually formed at the surface of lakes or (2) orthotropic or fully anisotropic as in the case of columnar ice formed at the lower depths of lakes. Further, the multiyear ice may consist of homogeneous and orthotropic ice layers in various orientations. There are insufficient data to isolate all the factors affecting the behavior of multiyear ice (ref. 1). An alternate approach is computational simulation through the use of MFIM and integrated composite mechanics available in the computer code ICAN (Integrated Composite Analyzer, ref. 4).

The integrated procedure for the computational simulation of the formation of ice and the behavior of its properties is shown in figure 2. The simulation begins with a body of water (bottom left of fig. 2). A finite-element model is developed for the body of water. A transient heat transfer analysis (top left of fig. 2) is conducted and results in a layer-by-layer ice formation with time. The heat transfer analysis provides temperature profiles through each ice layer at all times. The mechanical properties of each layer are then simulated using a multifactor interaction model (top right of fig. 2). The global properties of the ice block are predicted using ICAN (bottom right of fig. 2).

DESCRIPTION OF COMPUTATIONAL SIMULATION CODES

As shown in figure 2, two computer codes are used: (1) CSTEM (Coupled Structural/Thermal/ElectroMagnetic Analysis/Tailoring, ref. 5) to simulate the ice formation layer by layer and (2) ICAN (Integrated Composite Analyzer, ref. 4) to simulate the mechanical and thermal properties of ice at all its scales (layers and the ice block). A brief description of the capabilities of each code follows to demonstrate their suitability to computationally simulate the formation and the subsequent behavior.

Ice Formation: CSTEM

As illustrated in figure 3, CSTEM is an integrated, multidisciplinary, three-dimensional, finite-element code with sequentially coupled, single-discipline (heat transfer, structural, acoustic, electromagnetic) codes including those for integrated composite mechanics and optimization methods. It computationally simulates the coupled response of layered multimaterial composite structures subjected to simultaneous multidisciplinary loads. The composite material behavior and structural response are determined at its various inherent scales: micro, ply (ice layer), laminate (ice block), and component (multiyear ice). CSTEM has ICAN as a module to characterize the material behavior at various composite scales. The mechanical and thermal properties at the micro scale are considered to be nonlinearly dependent on various parameters such as time and temperature.

For the present investigation, CSTEM was used for the transient heat transfer analysis. It was also used to simulate the layer-by-layer ice properties by coupling it with the composite analyzer ICAN; CSTEM contains a heat transfer analysis capability for steady state and transient analyses. This capability allows one to obtain temperature distributions in a structure for either linear or nonlinear heat transfer problems, including conduction, convection, and radiation. The nonlinearities in the problem may include temperature-dependent properties. The thermal properties are computed and updated using the ICAN module. The temperature distributions can, in turn, be used to generate thermal loads in a stress analysis. The multitude of capabilities in CSTEM make it useful for simulating the formation of ice under constantly changing environmental conditions, using a nonlinear iterative loop.

The CSTEM code is versatile in that, if desired, a structural analysis can be performed within it simultaneously with the ice formation. The material properties of ice for all types of analyses in CSTEM can be input at its lower scales (in this case, layers) as it forms. The code automatically computes the material properties required for global/structural thermal analyses at higher ice scales (the ice block) using composite laminate theories embedded in the ICAN module.

Ice Material Behavior: ICAN

Based on composite micromechanics and laminate theories, ICAN simulates the mechanical and thermal properties at various scales (constituents, ply, and laminate) of a composite structure, starting from the room temperature properties of the constituents. Using an iterative approach, the MFIM is employed at its lowest material scale to simulate the degradation in material properties due to applied temperature, time, and environmental effects, as shown on the left side of figure 4. The ICAN code thus makes it possible to automatically compute the multiscale composite properties of any combination of multilayered, multimaterial composite configurations as well as of the degraded configurations at various stages of the composite life cycle. The room temperature properties of the lowest scale constituent materials are automatically extracted from the ICAN resident data bank which can be augmented for properties of new materials. This feature results in a considerable saving of the time required for searching and inputting the composite material property data.

For orthotropic and anisotropic forms, ICAN further breaks down the layers into a composite fiber/matrix unit cell. This representation allows the simulation of anisotropic ice properties at different orientations. In the present investigation, the ICAN code is demonstrated for homogeneous layers. The layers, however, have different properties because of temperature differences.

DEMONSTRATION OF COMPUTATIONAL SIMULATION

The description of a case demonstrating the formation of ice, the simulation model, and the results follows.

Case Description

The schematic of an illustrative ice formation process is shown in figure 5. A body of water initially at room temperature (70 °F) is exposed to an environmental temperature of 0 °F. The boundary conditions simulate a semi-infinite body of water in its horizontal plane. At the top surface, heat is dissipated by free convection from the water to the cooler atmosphere. The magnitude of the coefficient of convection heat transfer h is also shown in figure 5.

Simulation Model

A finite-element model consisting of 125 eight-noded brick elements was developed using CSTEM, as shown in figure 6. The thermal material properties, thermal conductivity, and coefficient of heat convection were considered temperature dependent. A nonlinear transient heat transfer analysis was conducted on a layer-by-layer basis. As the top surface of the body of water starts to cool (below the freezing temperature of 32 °F), ice begins to form. As water becomes ice, heat equivalent to the latent heat is released to the surroundings. To simulate the heat release, a temperature-dependent specific heat was used. The specific heat equivalent to the latent heat was used for the one-degree temperature difference from 31 to 32 °F. At this temperature, the ice specific heat was used (ref. 6). Heat transfer also occurs within the body of water as a result of the free convection of water caused by the thermal gradient. To simulate this effect, the equivalent thermal conductivity of water was calculated based on the free-convection heat transfer film coefficient.

Results

The temperature of the water at various depths is shown in figure 7. There is a rapid decrease in the top surface temperature at the beginning. The top layer of water begins to change into ice at about 3 hr. The rate of the temperature decrease slows with time, almost reaching the steady state after 12 hr. Figure 7 also shows time-dependent temperatures at two water depths. The rate of the temperature decrease is lower at greater depths. Figure 8 shows the temperature contours throughout the body of water after 13 hr. Ice has been formed for temperature contours at and below 32 °F. The time history of this ice formation is shown in figure 9. Ice has formed in several layers at different times. After about 12 hr, the increase in ice thickness becomes negligible as the steady state is reached. The temperatures that affect the ice behavior at a given time and water depth are shown in figure 7.

Test data are available for the modulus of elasticity and Poisson's ratio (ref. 1), thermal conductivity and the thermal expansion coefficient (ref. 7), and for tensile strength (ref. 8). The mechanical and thermal property exponents in equation (1) were calculated using data from a single test at 0 °F. The value of the exponent was calibrated to be 0.2 for the modulus of elasticity and tensile strength and 0 for Poisson's ratio. The exponent for density, thermal conductivity, and thermal expansion coefficient was determined to be 0.05. The MFIM was then used to predict the entire range of mechanical and thermal properties of the ice.

As expected, as the ice temperature decreased, its modulus of elasticity (fig. 10) and tensile strength (fig. 11) increased. Poisson's ratio (fig. 12) was assumed to remain constant with temperature. The density (fig. 13) decreased with decreasing temperature; that is, the colder the ice got, the lighter it became. The thermal conductivity (fig. 14) increased slightly as the ice temperature decreased to about 25 °F and increased at a lower rate after that. The thermal expansion coefficient (fig. 15) behaved opposite to the thermal conductivity; there was a relatively small-to-negligible change for the thermal properties and for density.

Next, using laminated composite mechanics, selected mechanical and thermal properties were simulated for the entire ice block as a function of time. The modulus of elasticity (fig. 16), tensile strength (fig. 17) and thermal conductivity (fig. 18) of the entire ice block increased with time as new ice layers were added to the ice block. The density (fig. 19) and thermal expansion coefficients (fig. 20) of the ice block mildly decreased with time as it increased in size.

The important point is that the material behavior of the ice block was strongly dependent on the environmental temperature and the layer-by-layer formation of ice. Hence, it is crucial that the prevailing environmental influences on the ice be incorporated in the evaluation of its behavior. Two computer codes described and used are capable of simulating all these influences on the ice. The results demonstrated the effectiveness of these codes in capturing the ice formation process and characterizing its behavior in prevailing transient environments.

CONCLUSIONS

This report described the computational methods used to simulate the layer-by-layer formation of ice and to characterize its material behavior. A multifactor interaction model was presented for assessing the material behavior of ice formed under prevailing environments over a period of time. The model is general in that it is applicable to all types of ice, isotropic or anisotropic, formed under various conditions. The enabling computer codes were demonstrated for a sample case, which illustrated the procedure and the importance of a layer-by-layer simulation of the formation of ice and its behavior under the prevailing environments. The results showed that the modulus of elasticity and tensile strength of ice layers and of the entire ice block increase with time as the ice temperature decreases; also, the density of the ice layers and of the entire ice block decrease. Using computer codes, results such as these can be generated in a very short time. Collectively, the results demonstrated that the formation process and the properties of ice can be computationally simulated—making it a cost-effective way.

REFERENCES

1. Sanderson, T.J.O.: Ice Mechanics: Risks to Offshore Structures. Graham and Trotman Publishing Company, London, 1988.
2. Chamis, C.C.; and Murthy, P.L.N.: The NASA Lewis Reference Guide To Computer Codes of the Structural Mechanics Branch. NASA Structures Division Document, NASA Lewis Research Center, Cleveland, OH, 1993.
3. Lee, H-J.; Gotsis, P.K.; and Murthy, P.L.N.: Metal Matrix Composite Analyzer (METCAN): User's Manual Version 4.0. NASA TM–105244, 1992.
4. Murthy, P.L.N.; and Chamis, C.C.: ICAN: Integrated Composite Analyzer. J. Compos. Technol. Res., vol. 8, no. 1, 1986, pp. 8–17 (also NASA TP–2515, 1986 and AIAA Paper 84–0974, 1984).
5. Singhal, S.N.; Murthy, P.L.N.; and Chamis, C.C.: Coupled Multi-Disciplinary Composites Behavior Simulation. NASA TM–106011, 1993.
6. Thermal Network Modeling Handbook. (TRW–14690–HOO3–RO–OO, TRW Systems Group, NASA Contract NAS9–10435), NASA CR–144418, 1972.
7. Dorsey, N.E.: Properties of Ordinary Water-Substance in All Its Phases: Water Vapor, Water, and All the Ice. Reinhold Publishing Corporation, New York, 1940.
8. Xian, X. et al.: An Experimental Evaluation of the Tensile Strength of Impact Ice. J. Mater. Sci. Lett., vol. 8, Oct. 1989, pp. 1205–1208.x

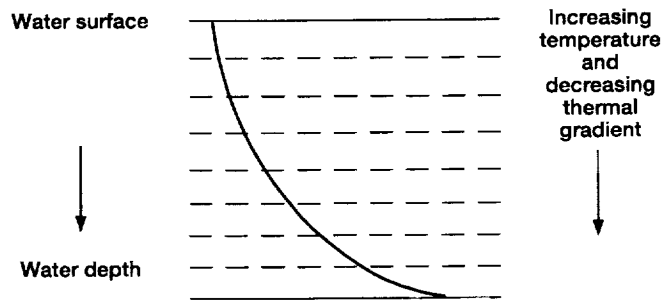

Figure 1.—Generic temperature profile during ice formation process. Ambient air temperature, < 32 °F.

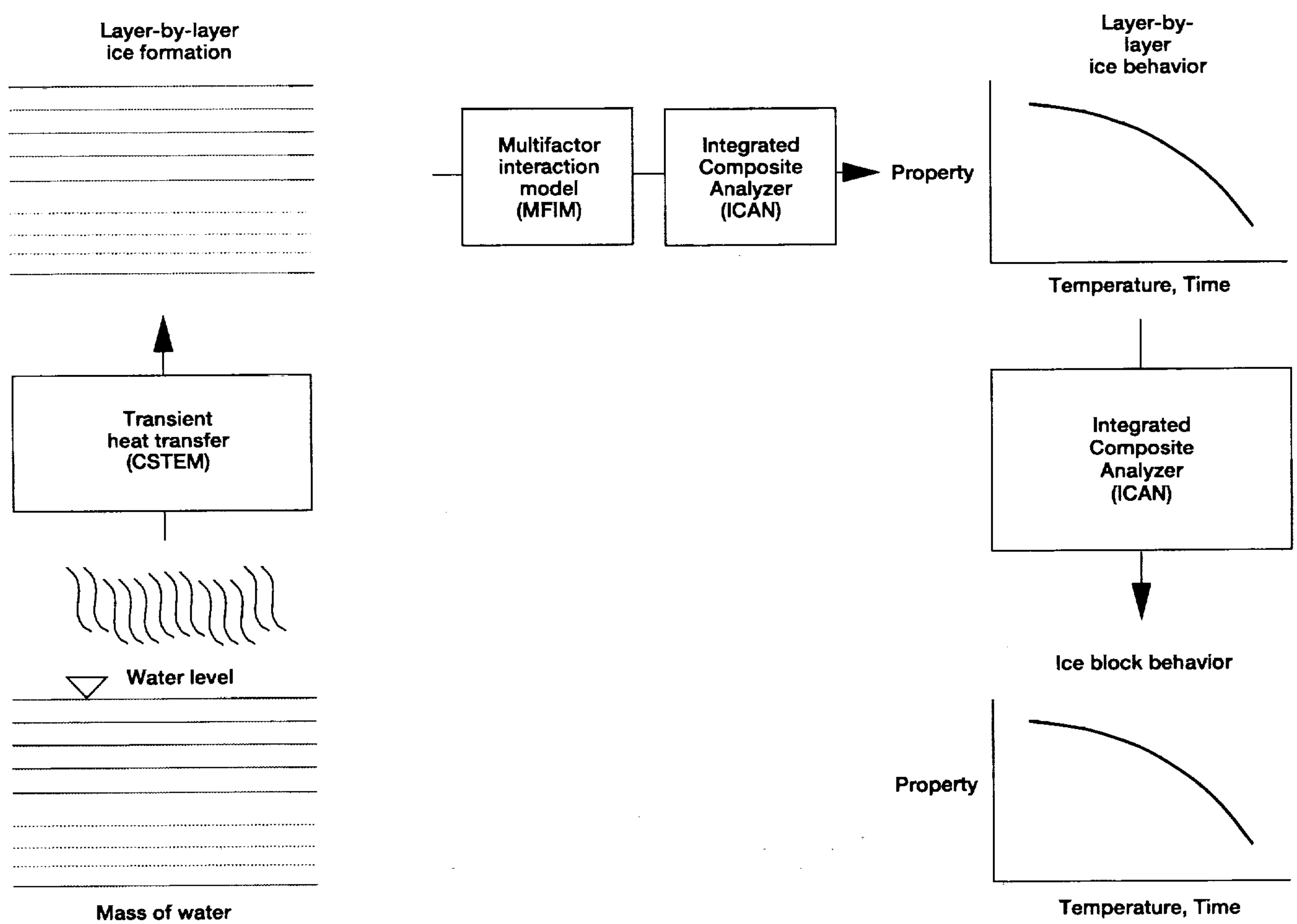

Figure 2.—Integrated procedure for computational simulation of ice formation and behavior.

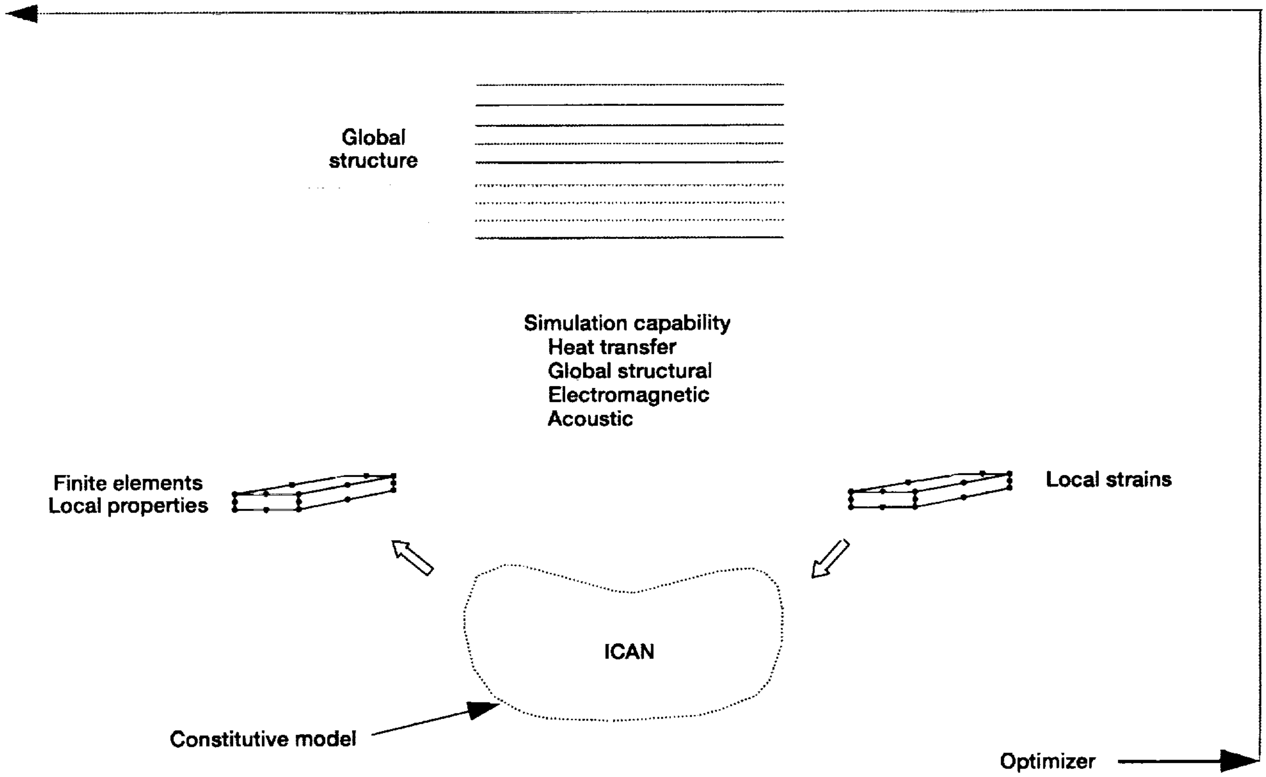

Figure 3.—CSTEM analysis and tailoring coupled with Integrated Composite Analyzer

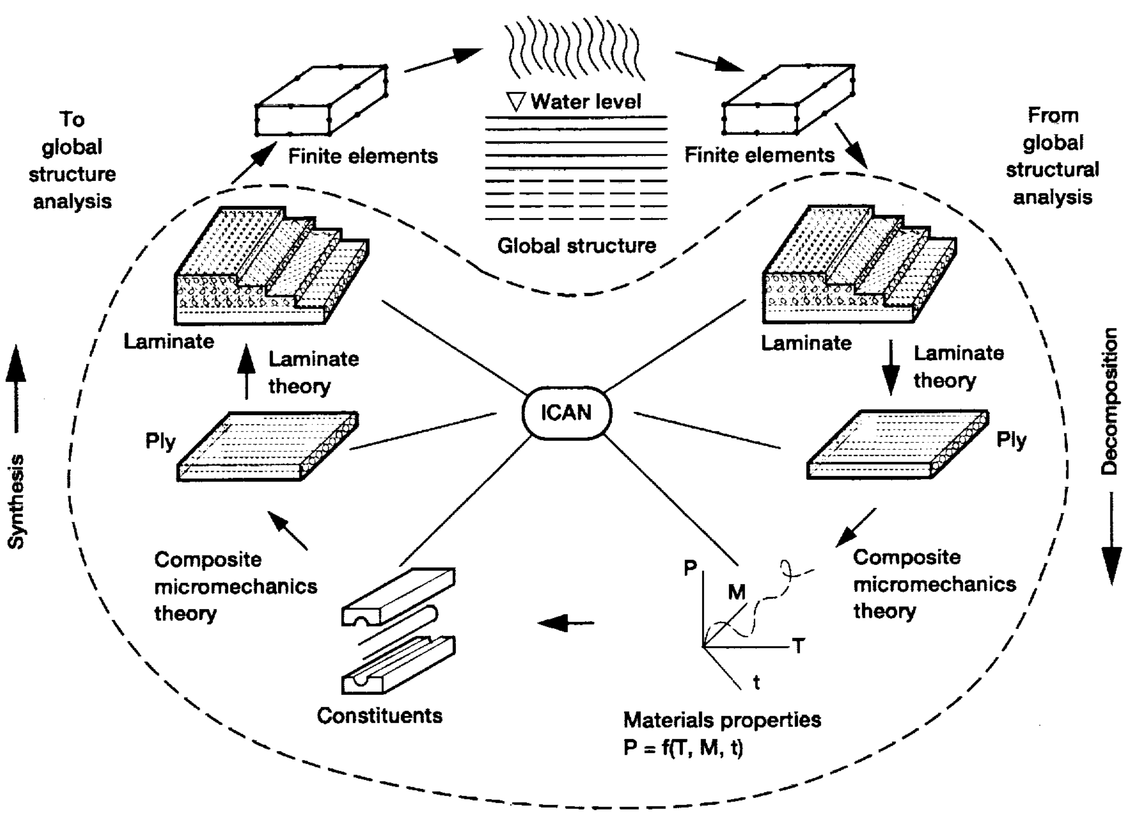

Figure 4.—Integrated composite analyzer (ICAN).

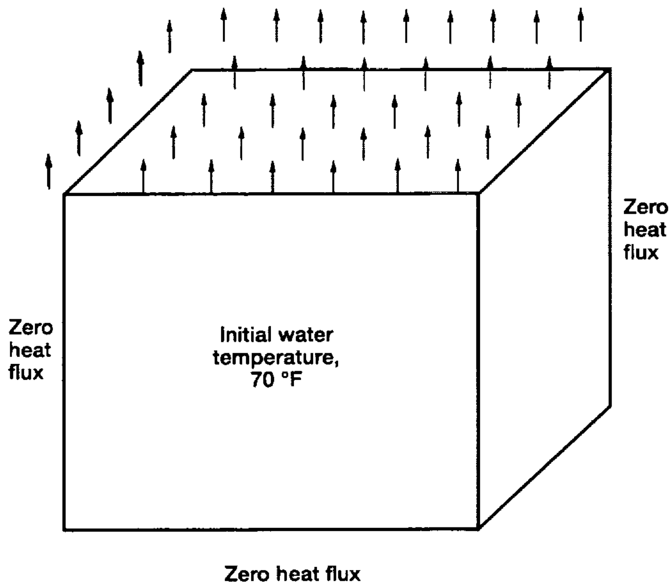

Figure 5.—Semi-infinite body of water exposed to subfreezing temperature, 0 °F. Coefficient of convection heat transfer, h, 10 Btu/hr-ft^2-°F.

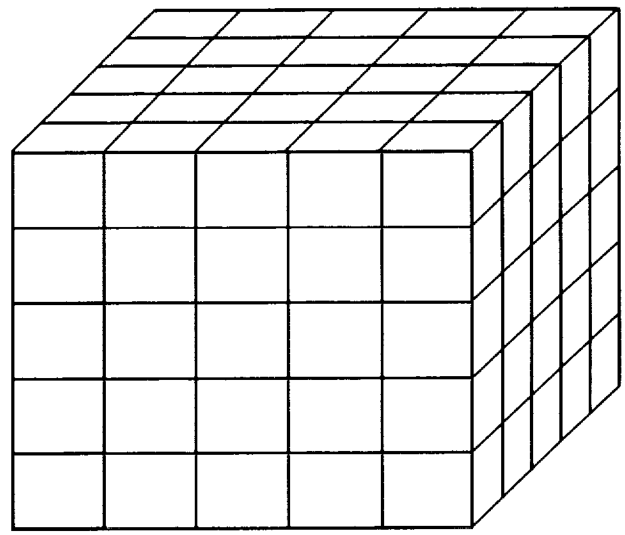

Figure 6.—Finite-element model for ice formation process (125 8-noded brick elements).

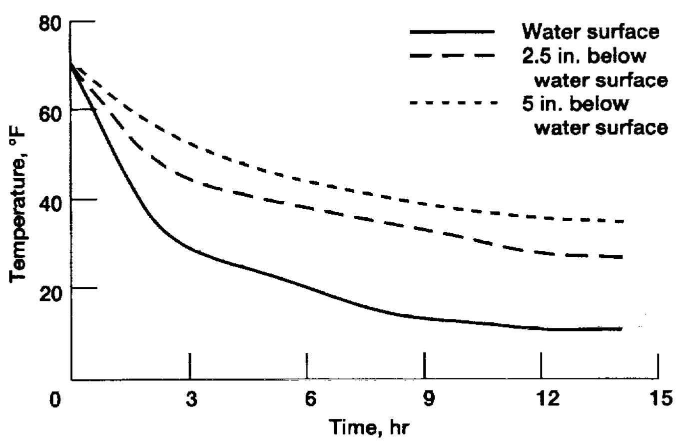

Figure 7.—Time history of water temperature. Ambient temperature, 0 °F; initial water temperature, 70 °F.

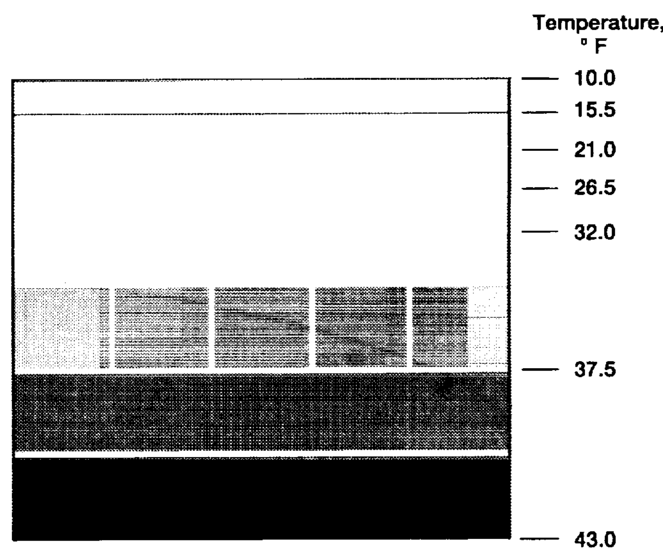

Figure 8.—Temperature profile of ice layers after 13 hr.

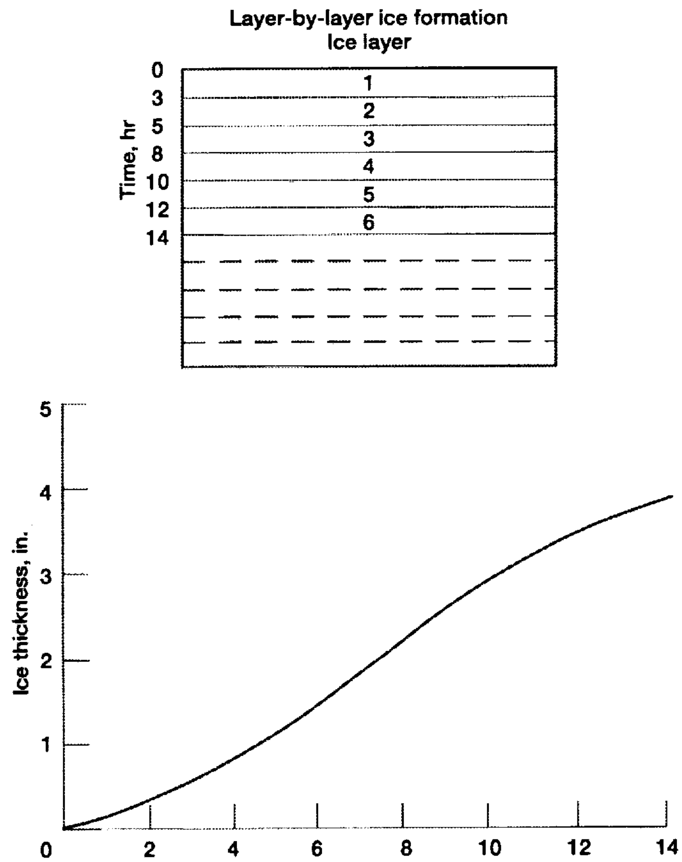

Figure 9.—Time history of ice formation. Ambient temperature, 0° F; initial water temperature, 70° F.

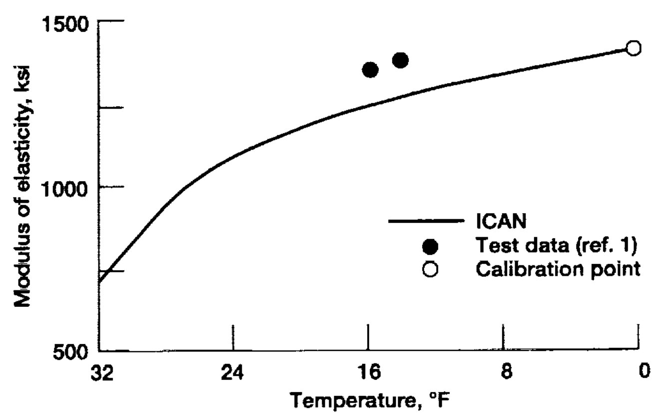

Figure 10.—Temperature variation of modulus of elasticity of ice layers.

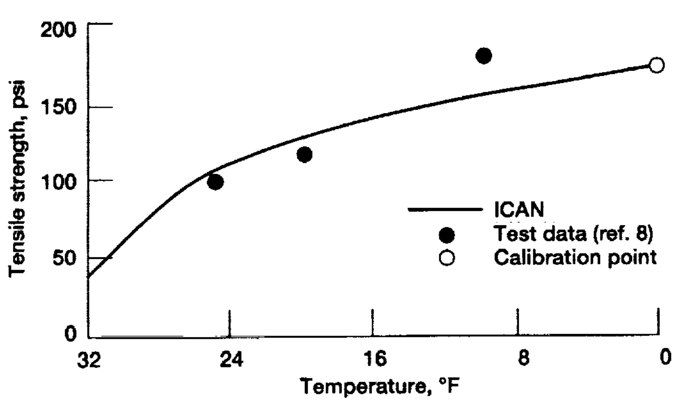

Figure 11.—Temperature variation of tensile strength of ice layers.

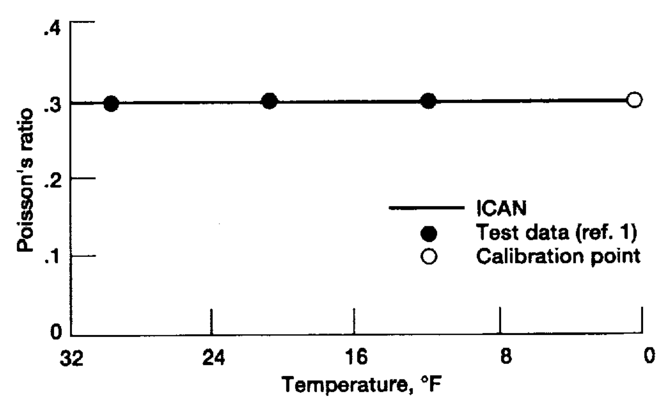

Figure 12.—Temperature variation of Poisson's ratio of ice layers predicted by ICAN.

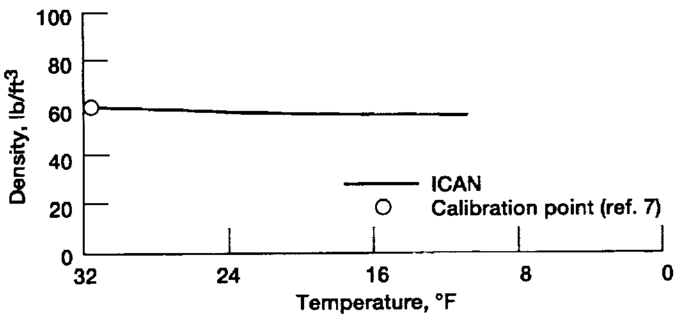

Figure 13.—Temperature variation of density of ice layers predicted by ICAN.

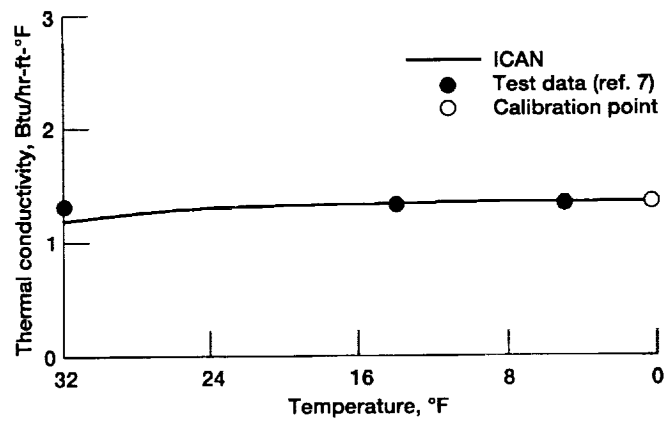

Figure 14.—Temperature variation of thermal conductivity of ice layers.

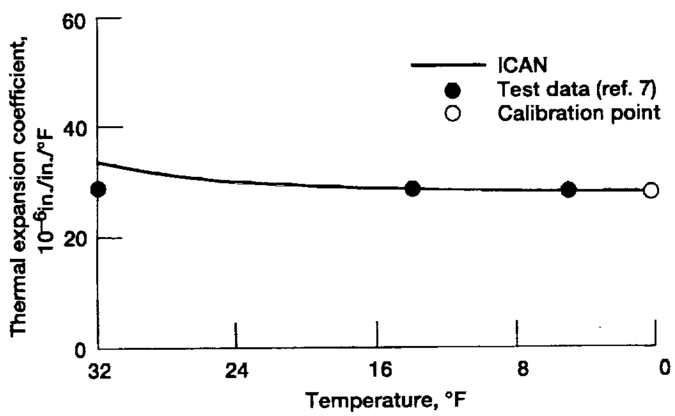

Figure 15.—Temperature variation of thermal expansion coefficient of ice layers.

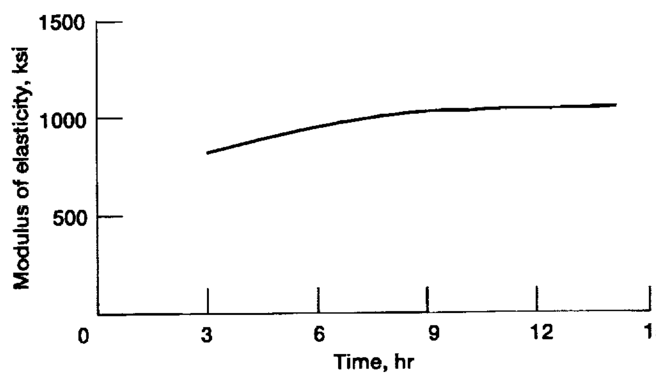

Figure 16.—Time history of modulus of elasticity of entire ice block as predicted by ICAN.

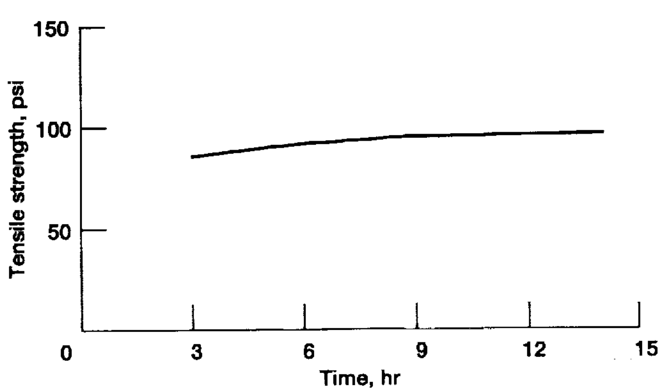

Figure 17.—Time history of tensile strength of entire ice block as predicted by ICAN.

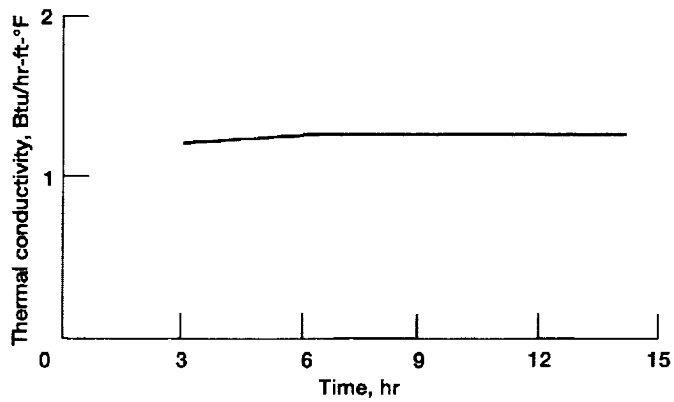

Figure 18.—Time history of thermal conductivity of entire ice block as predicted by ICAN.

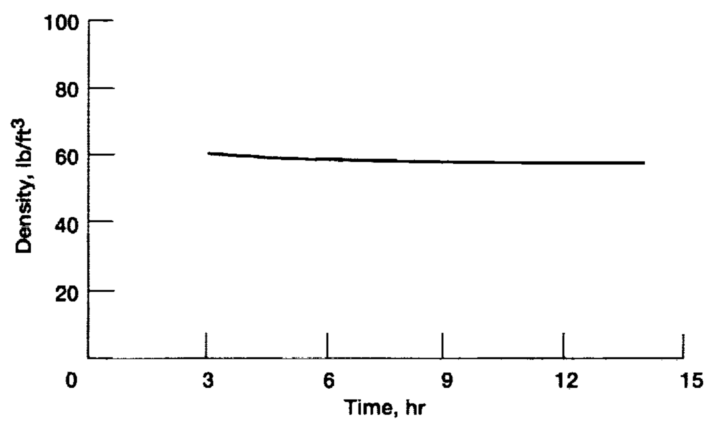

Figure 19.—Time history of density of entire ice block as predicted by ICAN.

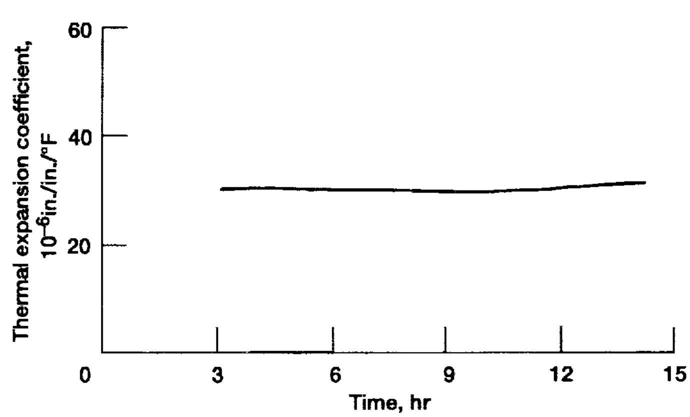

Figure 20.—Time history of thermal expansion coefficient of entire ice block as predicted by ICAN.

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13. ABSTRACT ***(Maximum 200 words)***

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